only free parameter. The solid line in Fig. 2 is achieved with ϑ = 0.75 and shows excellent agreement with the measurements for α_{MZ}.

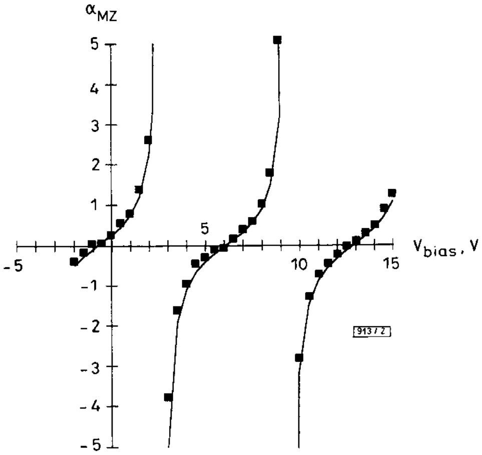

Fig. 2 *α parameter for MZ modulator as function of applied bias voltage*

■ experimental results
——— fitted theoretical value with chirp parameter ϑ = 0.75

Conclusions: Based on known theory about the α parameter of MZ modulators [2] and using the measurement method for it [5], a simple and accurate method for the evaluation of the chirp parameter ϑ of an MZ modulator is presented. Theory and experiment have shown good agreement. In the example presented, the MZ modulator has a chirp of ϑ = 0.75, which is reasonable for this type of modulator.

 18 July 1994

Electronics Letters Online No: 19941005

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High frequency optical subcarrier generator

X.S. Yao and L. Maleki

Indexing terms: Electro-optical devices, Optical modulation

The authors describe an electro-optical oscillator capable of generating high stability optical signals at frequencies up to 70GHz. Signals as high as 9.2GHz were generated with an optical wavelength of 1310nm using the oscillator, and a comb of stable frequencies was produced by modelocking the oscillator.

In advanced photonic analogue communication systems, high frequency optical subcarrier generation is essential for photonic signal up and down conversions [1]. In this Letter, we report a novel optical subcarrier generator, called an electro-optic (E/O) oscillator, that is capable of generating an up to 70GHz (limited by the speed of E/O modulator and photoreceiver) high stability optical subcarrier. By modelocking the oscillator, a comb of stable high frequencies can also be generated.

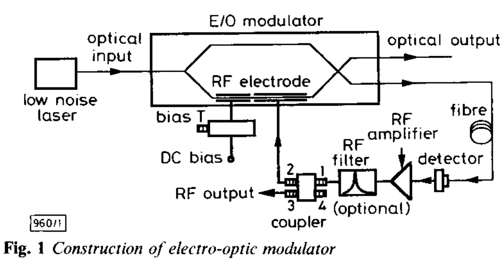

Fig. 1 *Construction of electro-optic modulator*

The E/O oscillator [2] is described in Fig. 1. Light from one of the output ports of the modulator is detected by the photodetector and then is amplified, filtered, and fed back to the electrical input port of the modulator. If the modulator is properly biased and the open loop gain of the feedback loop is properly chosen, self-electro-optic oscillation will start. Because both optical and electrical processes are involved in the oscillation, both optical and electrical signals will be generated simultaneously.

We built two such E/O oscillators using two different modulators. In the first oscillator, the Mach-Zehnder modulator has a bandwidth of 8GHz and a half-wave voltage V_π of ~17V. It has an internal bias control circuit that automatically sets the modulator bias at 50% of the transmission peak. The photoreceiver has a bandwidth of 12GHz and a responsivity of ~0.35A/W. The amplifier has a total electrical power gain of 50dB, a bandwidth of 5GHz centred around 8GHz, and an output 1dB compression of 20dBm. The input and output impedances of all electrical components in the loop are 50Ω. The loop length is ~9m.

Studies [3] have shown that depending on the biasing point of the modulator, the E/O oscillator may be bistable, oscillatory, or chaotic. However, the E/O modulator used above has a fixed bias point that cannot be adjusted. To investigate the effect of bias point on the EJO oscillator, we built another E/O oscillator with a modulator that has an independently controlled bias electrode. However, this modulator is slower (1GHz bandwidth) and has a half-wave voltage of ~10V.

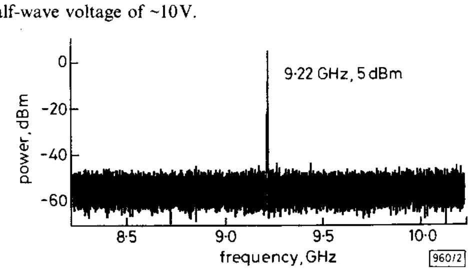

Fig. 2 *Generated 9.22Hz oscillation observed on an RF spectrum analyser*

With the first E/O oscillator, we demonstrated in the laboratory the first high frequency electro-optic oscillator that generated an optical subcarrier and the accompanying electric signal up to 9.2GHz, using a diode pumped YAG laser at 1310nm. The generated 9.2GHz oscillation signal is shown in Fig. 2. The power of this self-oscillation measured at the electrical output port is 5.33dBm and the bandwidth is ~100Hz. A frequency drift of ~30kHz was observed of the self-oscillation in a 10 min period and is probably due to the loop length fluctuation caused by temperature and acoustic vibration. The frequency drift and bandwidth are expected to be reduced using a novel loop length stabilisation technique (to be discussed elsewhere). It was interesting to observe that the oscillator self-oscillated with a 'single mode' even though no electrical filter was placed in the loop. However, multimode operation of the oscillator was also observed when the loop gain was sufficiently high.

Using the second E/O oscillator, we investigated the power spectra of the oscillator as a function of bias voltage and observed that depending on the bias voltage, the oscillator either oscillates with a single mode or multimodes of different mode spacings. As expected, these mode spacings are integers of the oscillator's natural mode spacing (the inverse of the loop delay time). The bandwidth of each oscillation peak was less than 10Hz and the centre frequency fluctuation was less than 5.5kHz/s.

Stable multimode oscillation of the E/O oscillator can be realised by means of modelocking. Similar to the case of a modelocked laser, if a stable driving signal has a frequency that is close to an integer number of the natural mode spacing, modes with a spacing close to the driving signal frequency will be locked together in phase and the oscillator's mode spacing will be held fixed by the frequency of the driving signal, in spite of loop delay fluctuations. We were able to modelock the E/O oscillator with a driving signal of as little as –6dBm applied to the bias port of the E/O modulator. We confirmed the modelocking by observing the output signal of the oscillator in the time domain on an oscilloscope: Before the oscillating modes were modelocked, the phase of the modes fluctuated independently and the signal on the oscilloscope was a low level noise. By gradually increasing the driving power to about –6dBm, a strong oscillatory square-like wave suddenly appeared, indicating that modes were phaselocked together.

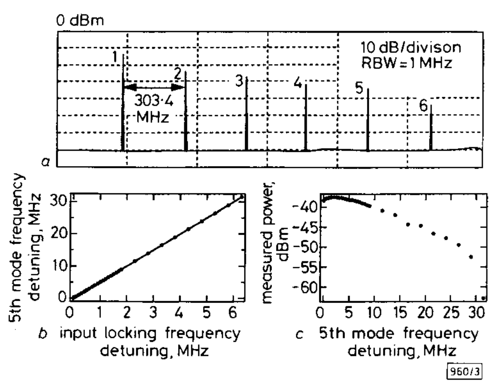

Fig. 3 *Modelocked E/O oscillator characteristics*

a Oscillator RF spectra measured at the optical output port using a photodetector and a spectrum analyser. A driving signal of f_d = 303.7MHz was injected to the E/O modulator from the bias T shown in Fig. 1. Signal levels were 30dB higher when measured at the RF output port

b Detuning Df_5 of the 5th mode as a function of the detuning Df_d of the driving signal; Curve-fitting yields $Df_5 = 5Df_d$

c RF power of the 5th mode as a function of detuning

Fig. 3*a* shows the power spectrum of the oscillator when it was modelocked by a 2dBm driving signal of 304MHz. As can be seen, there were six modes oscillating, and the mode spacing is also 304MHz. After examining each mode individually we found that the frequency of each mode was stabilised to the level of the driving signal and no frequency drift was observed. When the driving frequency was changed slightly, the frequency of each mode followed the change accordingly. Fig. 3*b* shows how the frequency of the 5th mode changed as a function of driving frequency detuning and confirms our expectation that the *n*th mode frequency detuning equals *n* times the driving frequency detuning. Fig. 3*c* shows the RF power of the 5th mode as a function of frequency detuning. It seems that the further away the mode is from its natural oscillation frequency, the lower is the oscillation RF power. It is interesting to note that this curve is not symmetric: when the detuning frequency was less than 0, the 5th mode oscillation abruptly stopped. The reason for this phenomenon is not yet clear to us.

Our analysis indicates that when $V_\pi < (\alpha\rho P_{in}/2)\pi R$ is satisfied, no amplifier is required in the feedback loop to sustain the electro-optic oscillation. In the equation, α and R are the insertion loss (fractional) and input impedance of the modulator, respectively, ρ is the responsivity of the detector, and P_{in} is the input optical power. For $R = 50\Omega$ and $(\alpha\rho P_{in}/2) = 10$mA, V_π must be less than 1.57V. Because it is relatively easy to match the velocity of the electric driving signal over a narrow bandwidth with that of light, a high frequency modulator with such a small V_π over a narrow band may be possible.

In summary, we have generated optical subcarriers as high as 9.2GHz using an E/O oscillator and a comb of stable frequencies by modelocking an oscillator. Currently, we are investigating the noise properties of the oscillator and developing a novel technique for stabilising the feedback loop of the oscillator.

Acknowledgments: This work represents the results of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. We thank Dr. Calhoun for lending us an electro-optic modulator.

21 July 1994
Electronics Letters Online No: 19941033

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Highly doped 1.55µm $Ga_xIn_{1-x}As/InP$ distributed Bragg reflector stacks

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Indexing terms: Distributed Bragg reflector lasers, Gallium indium arsenide, Indium phosphide, Reflection modulators

The authors have investigated 20 period lattice matched mirror stacks doped to $5 \times 10^{18}cm^{-1}$ and $10^{19}cm^{-1}$ at 1.55µm in $Ga_xIn_{1-x}As$/InP and have obtained greater than 95% reflectivity over 100nm and peak reflectivities up to 98%.

1.55µm mirror stacks are important for devices such as lasers and asymmetric Fabry Perot modulators. The use of semiconductor distributed Bragg reflector stacks allows monolithic integration, hence eliminating the requirement for post-growth processing, and simplifying the design. At shorter wavelengths the large refractive index differences between the available DBR stack materials allow fewer periods to be used. Combined with the larger absorption coefficients in the active region and the better known technology, very good devices have been fabricated [1]. Very few micro-resonator modulators operating at 1.55µm have been reported [2–4]. For highly reflecting mirror stacks, a large retractive index difference between the two alternate layers in the stack is required. At